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Cassini/Huygens Science Instruments, Spacecraft, and Mission

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The Cassini spacecraft will take 18 scientific instruments to Saturn. After launch and a seven-year cruise, Cassini will arrive at Saturn and separate into a Saturn orbiter and an atmospheric probe, called Huygens, which will descend to the surface of Titan. The orbiter will orbit the planet for four years, making close flybys of five satellites, including multiple flybys of Titan. Communication with Earth is at X-band; the maximum downlink rate from Saturn is 166×10^3 bps. Orbiter instruments are body mounted; the spacecraft must be turned to point some of them toward objects of interest. The orbiter carries 12 instruments. Optical instruments provide imagery and spectrometry. Radar supplies imaging, altimetry, and radiometry. Radio links contribute information about intervening material and gravity fields. Other instruments measure electromagnetic fields and the properties of plasma, energetic particles, and dust particles. The probe is spin stabilized. It returns data via an S-band link to the orbiter. The probe's six instruments include sensors to determine atmospheric physical properties and composition. Radiometric and optical sensors will produce data on thermal balance and obtain images of Titan's atmosphere and surface. Doppler measurements between probe and orbiter will provide wind profiles. Surface sensors will measure impact acceleration, thermal and electrical properties, and, if the surface is liquid, density and refractive index. This design will enable Cassini to determine the composition; the physical, morphological, and geological nature; and the physical and chemical processes of the atmospheres, surfaces, and magnetosphere of the Saturnian system. This paper briefly describes the Cassini mission and spacecraft and, in somewhat more detail, the scientific instruments.

Introduction

CASSINI consists of a Saturn orbiter plus a Titan atmospheric probe. The probe is named Huygens after the seventeenth century Dutch astronomer Christiaan Huygens, who discovered Titan and first recognized that the two "handles" of Saturn, seen by Galileo, are really a ring. Cassini is named after the seventeenth century Italian/French astronomer Jean Dominique Cassini, who recognized that there is more than one ring and discovered four more satellites of Saturn: Iapetus, Rhea, Dione, and Tethys.

Cassini is the last of the large planetary spacecraft currently planned. Planetary visits in our solar system began with the first Mariner spacecraft, which flew by Mercury, Venus, and Mars. Flybys were followed up with orbiting spacecraft (Pioneer, Mariner, Viking, Venera, Magellan, Galileo, Mars Global Surveyor), which studied the solar system in more detail. Planetary flybys and orbiters were followed by studies in greater depth using atmospheric probes and surface landers: Surveyor, Viking, Venera, Vega, Galileo Probe, Mars Pathfinder. Perhaps the most famous planetary spacecraft are Voyagers 1 and 2, which surveyed the solar system with flybys of the outer planets and now continue in the heliosphere beyond.

The flybys of Saturn by Pioneer 11 in 1979 and by Voyagers 1 and 2 in 1980 and 1981 will now similarly be followed by an in-depth study with Cassini's planetary orbiter and atmospheric and surface probe.

This paper provides brief accounts of the Cassini mission and spacecraft and a more detailed description of the scientific instruments. Among the reports of previous work on or leading to Cassini are Refs. 1–15.

Scientific Objectives

Objectives of the Cassini mission are 1) to determine the elemental, molecular, isotopic, and mineralogical compositions of Saturn, Titan, the smaller satellites, and the rings of the Saturnian system; 2) to determine the physical, morphological, and geological nature of these objects; 3) to determine the physical and chemical processes operating in the atmospheres of Saturn and Titan, including their dynamics; 4) to determine the physical and chemical processes operating on the surfaces of the rings and satellites of the system; 5) to determine the physical and dynamical properties of the rings; 6) to determine the physical and dynamical properties and the composition of Saturn's magnetosphere and its interactions with the rings, satellites, and solar wind, and to obtain maps of the magnetosphere; 7) to map the surfaces of Titan and the icy satellites at wavelengths from extreme ultraviolet to Ku-band radar; 8) to determine composition and mass distribution of ice and dust grains in the Saturnian system; 9) to measure plasma waves and radio emissions in the Saturnian system; 10) to examine the possibility of exobiology on Titan; and 11) to search for gravitational waves.

Mission

The Cassini mission is outlined in Refs. 16–19. Current plans are that the spacecraft will be launched Oct. 6, 1997, using a Titan IV/Centaur with solid rocket motor upgrades and a C3 (square of the escape velocity) of 18.1 km^2/s^2. It will use two gravity assists from Venus, one from Earth, and one from Jupiter (Fig. 1). The closest distance to the sun will be 0.68 AU. The Venus flybys will be in April 1998 and June 1999 at altitudes of 300 and 2200 km and relative speeds of 11.8 and 13 km/s, respectively. Earth flyby will be in August 1999 at an altitude of 500 km and a relative speed of 19 km/s. The Jupiter flyby will be in December 2000, with a closest approach of 140 Jupiter radii and a relative speed 11.6 km/s. The C3, flyby dates, altitudes, and speeds will vary somewhat if the launch date changes. Trajectory correction maneuvers will be needed before each flyby.

Cassini will search for gravitational waves at opposition after the Jupiter flyby. Limited scientific measurements will be made during the two years before the Saturn encounter. Cassini will reach Saturn in July 2004. The spacecraft will fly by the satellite Phoebe 19 days before the closest approach at a distance of about 50,000 km. The Saturn orbit insertion maneuver, requiring a velocity change (ΔV) of 0.61 km/s, will take place just before periapsis at 1.3 Saturn radii. The initial orbit has a period of about 150 days and an inclination of 17 deg (Fig. 2). A maneuver at first apoapsis ($\Delta V = 0.33$ km/s)

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will target the spacecraft for Titan flyby and raise its periapsis to 8.2 Saturn radii.

In November 2004 the Huygens probe will be spun up and released from the orbiter at 0.3–0.4 m/s relative velocity. Its V-infinity relative to Titan will be 6.1 km/s. It will coast for 22 days after separation and then enter the Titan atmosphere at about 18°N latitude and 209°E longitude on the daylight side.

The probe will be dormant from separation until it reaches an altitude of 1270 km. Probe accelerometers and a radio transmitter will then be turned on for measurements during entry. The probe will be aerodynamically decelerated to Mach 1.5 (approximately 400 m/s) at an altitude of about 180 km (Fig. 3). Heat shield and covers will then be jettisoned and a parachute will be deployed. Parachute opening should be complete at an altitude of 160 km. Chemical analysis of the atmosphere and other scientific measurements will begin at this altitude, and resulting data will be transmitted to the orbiter. Descent from 190 km to the surface will take 2–2.5 h. Because the main parachute would provide too slow a descent through the lower atmosphere, it will be jettisoned at an altitude of about 125 km and a smaller drogue parachute will be deployed. Winds may deflect the landing point by as much as 800 km. The probe will impact the surface at 5–6 m/s. If the probe survives impact, scientific measurements may be obtained on the surface. Line of sight to the orbiter for data relay will be available for at least 30 min after impact.

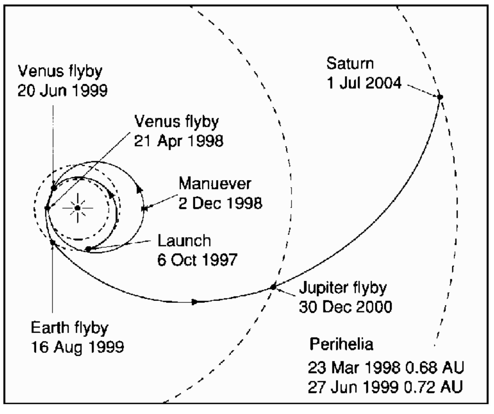

Fig. 1 Cassini interplanetary trajectory.

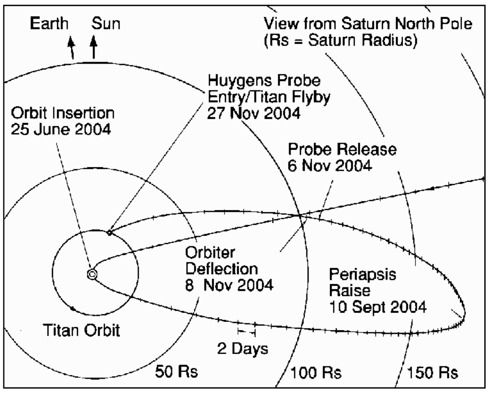

Fig. 2 Cassini initial orbit about Saturn.

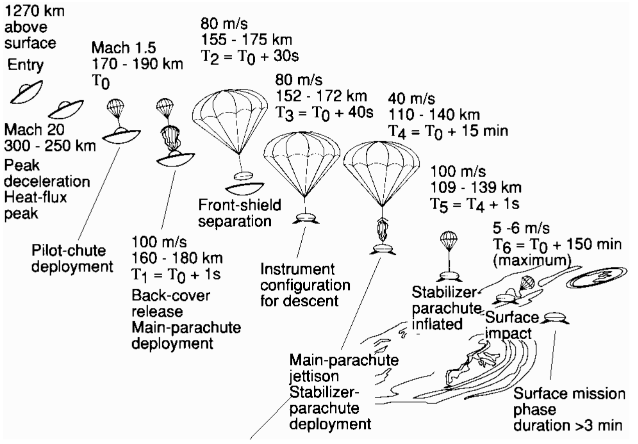

Fig. 3 Huygens Probe descent sequence.

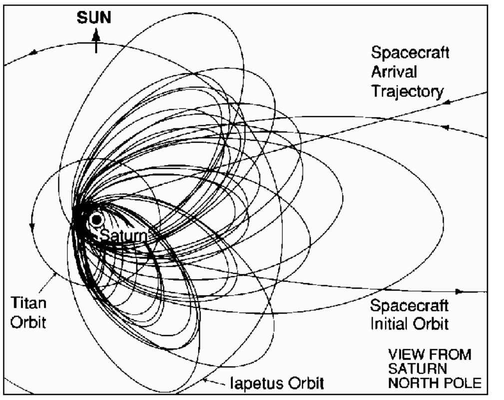

Fig. 4 Preliminary Cassini Saturn orbital tour (extract, not all orbits are shown).

After probe separation, a small maneuver will deflect the orbiter to fly by Titan at a minimum altitude of 1200 km and delay its closest approach. This maneuver will keep the orbiter and probe in line of sight while the probe descends through Titan's atmosphere, permitting probe data to be transmitted to the orbiter for storage and subsequent transmission to Earth.

The Titan flyby will lower the apoapsis of the orbiter and adjust its trajectory for another Titan encounter. The orbiter will continue on a four-year satellite tour, using repeated gravity assists from Titan and some small maneuvers to shape the trajectory to satisfy scientific objectives. A preliminary tour plan includes about 60 orbits of Saturn and 33 flybys of Titan (Fig. 4). Cassini orbital periods will be constrained to multiples or submultiples of Titan's period to ensure repeated flybys for gravity assist. During each flyby, Titan's gravity plus small spacecraft maneuvers will set the next orbit about Saturn. The orbital inclination first will be shifted downward to 0 deg and then upward to about 76 deg. Orbital periods will decrease to about 7 days and periapsis radius to 2.7 Saturn radii. The apoapsis direction will vary from 30 deg up to almost 180 deg from the Saturn–Sun line. Plans include flybys of the satellites Enceladus, Dione, Rhea, and Iapetus at a distance of about 1000 km and more distant flybys of these satellites and of Mimas and Tethys. Earth and Sun occultations by Saturn, its rings, and Titan are also planned. Nominal end of mission is June 2008.

This orbital plan is preliminary and will be revised before launch. It also may be modified later. For example, as the Titan flybys progress, the minimum flyby altitude will be lowered, according to current plan, to 950 km. As knowledge of the atmosphere is gained during the mission, the minimum altitude may be modified accordingly.

Spacecraft Description

Orbiter

The Cassini orbiter was originally planned as the second of a series of Mariner Mark II spacecraft, which would have high design commonality; the Comet Rendezvous Asteroid Flyby (CRAF) was to be the first.[6] In 1992, to reduce current-year costs, the CRAF mission and the Mariner Mark II concept were dropped, and the Cassini spacecraft was redesigned. The most important change for the instruments was deletion of the high-precision scan platform and the turntable on which many of the instruments were mounted, together with the booms that supported platform and turntable. In the new design, the whole spacecraft must, in general, be turned to point scientific instruments in the desired directions. Actuators were added to three instruments to permit them to rotate individually about one axis.

Figure 5 shows the current spacecraft design. The orbiter is 6.8 m long; its maximum diameter in launch configuration is 4 m. The

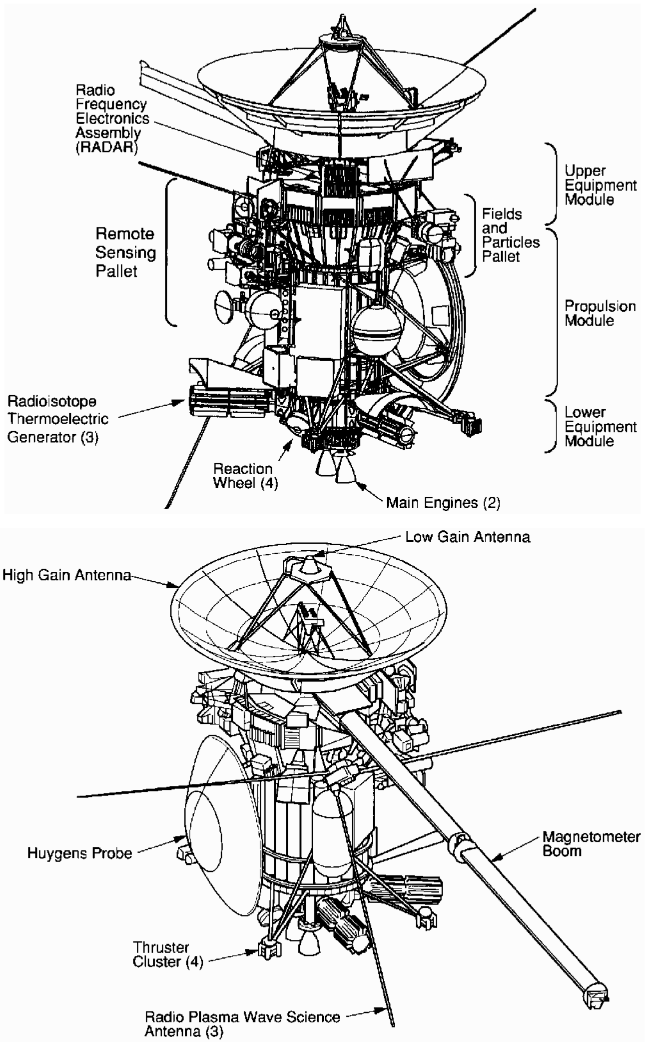

Fig. 5 Cassini spacecraft, deployed (two views).

total mass of Cassini at launch is approximately 5800 kg, which includes about 2700 kg of dry mass and 3100 kg of propellants.

The main body of the orbiter is a stack consisting of a lower equipment module, a propulsion module, an upper equipment module, and a high-gain antenna (HGA). The axis of this stack is the z axis of the orbiter. Attached to the stack are the Remote Sensing Pallet and the Fields and Particles Pallet with their scientific instruments as well as the Huygens Probe. The two pallets carry most of the scientific instruments. A few instrument assemblies are attached to the upper equipment module. The orbiter's 12-bay electronics bus is part of the upper equipment module. An 11-m magnetometer boom is mounted on the upper equipment module.

Figure 6 is a functional block diagram of the orbiter. In general, all elements whose failure could cause loss of the mission or loss of data from more than one scientific instrument are redundant. Onboard fault protection safeguards against many possible fault conditions. The design life of the spacecraft is 11 years. Electronic parts, in general, are radiation hard; digital components are immune to latch up and resistant to single-event upset. Identical 32-bit engineering flight processors are used by the attitude control and command and data subsystems and by two scientific instruments. The spacecraft will usually be operated via command sequences stored onboard. Thermal control is provided by reflective multilayer insulating blankets, radiators, reflective and absorptive paints, louvers, shades, radioisotope heater units, and electrical heaters.

Propulsion Module Subsystem

The propulsion module incorporates two redundant gimbaled 445-N engines with a specific impulse (I_{sp}) of 3020 N-s/kg (308 lbf-s/lbm). Bipropellent tanks hold about 3000 kg of nitrogen tetroxide and monomethylhydrazine. The reaction control subsystem includes four clusters, each containing four monopropellant hydrazine thrusters (0.2- to 1.0-N thrust). These thrust in a direction parallel to the HGA and in a direction perpendicular to it. The hydrazine tank holds 130 kg of hydrazine. Propellants are fed by helium pressurization. A retractable cover protects the main engines from damage by micrometeoroids.[20]

Power and Pyrotechnics Subsystem (PPS)

Three radioisotope thermoelectric generators (RTGs) provide 816 W of primary power at the beginning of the mission and 641 W at the end of the mission. From the RTGs, PPS distributes regulated 30-V dc power to orbiter users via a power bus and solid-state power switches, which incorporate damping of turn-on transients. The PPS provides firing current to the various pyrotechnic devices on command from the Command and Data Subsystem (CDS). It disposes of unused power from the constant-power RTG sources by radiating it to space via a resistance shunt radiator.[21]

Attitude and Articulation Control Subsystem (AACS)

The orbiter is three-axis stabilized. AACS provides attitude control either by reaction control wheels or by the thrusters, which also are used to unload the reaction control wheels.

Celestial attitude reference is supplied by a sun sensor and a stellar reference unit, which uses a charge-coupled device (CCD) sensor. Inertial reference is furnished by vibrating (nonrotating) gyros.[22,23]

Spacecraft pointing accuracy will be 2 mrad or better when the spacecraft is not thrusting or rotating. However, accuracy of pointing with respect to the object being observed is generally limited not by spacecraft pointing accuracy but by navigational uncertainties in the relative positions of the spacecraft and object.

AACS also controls orbiter translation through command of main engine and thruster valves. An accelerometer on the central z axis aids in controlling the duration of engine burns.

AACS contains redundant MIL-STD-1750A flight computers. It receives commands from the CDS via the CDS data bus and sends commands over its own data bus to AACS assemblies.

Radio Frequency Subsystem (RFS)

Communication between the orbiter and Earth is at X-band (7.2–8.4 GHz). Each redundant transponder includes a receiver and an exciter. Each redundant traveling-wave tube power amplifier provides 20-W radio frequency output. A hybrid power splitter connects either transponder to either power amplifier, and mechanical radio frequency switches permit connecting either power amplifier to any of the antennas. The RFS includes command detector units, telemetry modulation units, and interface control units, plus an ultrastable oscillator for the Radio Science investigation. The maximum planned data rate from Saturn is 166×10^3 bps using a 70-m ground antenna or a 70-m and a 34-m antenna together, 36×10^3 bps using a 34-m ground antenna only.

Antenna Subsystem

The orbiter antenna subsystem includes a 4-m parabolic HGA and two low-gain antennas. The antennas are fixed to the structure. An X-band feed is used for communication and for Radio Science. An S-band feed will receive telemetry from the Huygens probe after the probe is separated from the orbiter and will also be used for Radio Science. A Ka feed is provided for Radio Science. Five Ku feeds supply five beams for the radar experiment (Fig. 7).

For high telecommunication rates, the spacecraft must be oriented to point the HGA at Earth. At other times, especially while the spacecraft is in the inner solar system, the axis of the HGA will be pointed close to the Sun so the antenna will shade most of the spacecraft. During many maneuvers, the axis will point in the desired direction of thrust. When this happens, real-time telecommunication will be via a low-gain antenna at very low bit rates (generally 40 bps). Also, the HGA must point toward the Huygens probe when receiving telemetry from the probe, and, for observations with remote-sensing instruments, the spacecraft must point them toward the objects of scientific interest. The HGA cannot then be pointed at Earth. In these last two cases, no real-time communication with Earth is planned. Instead, data will be stored in the

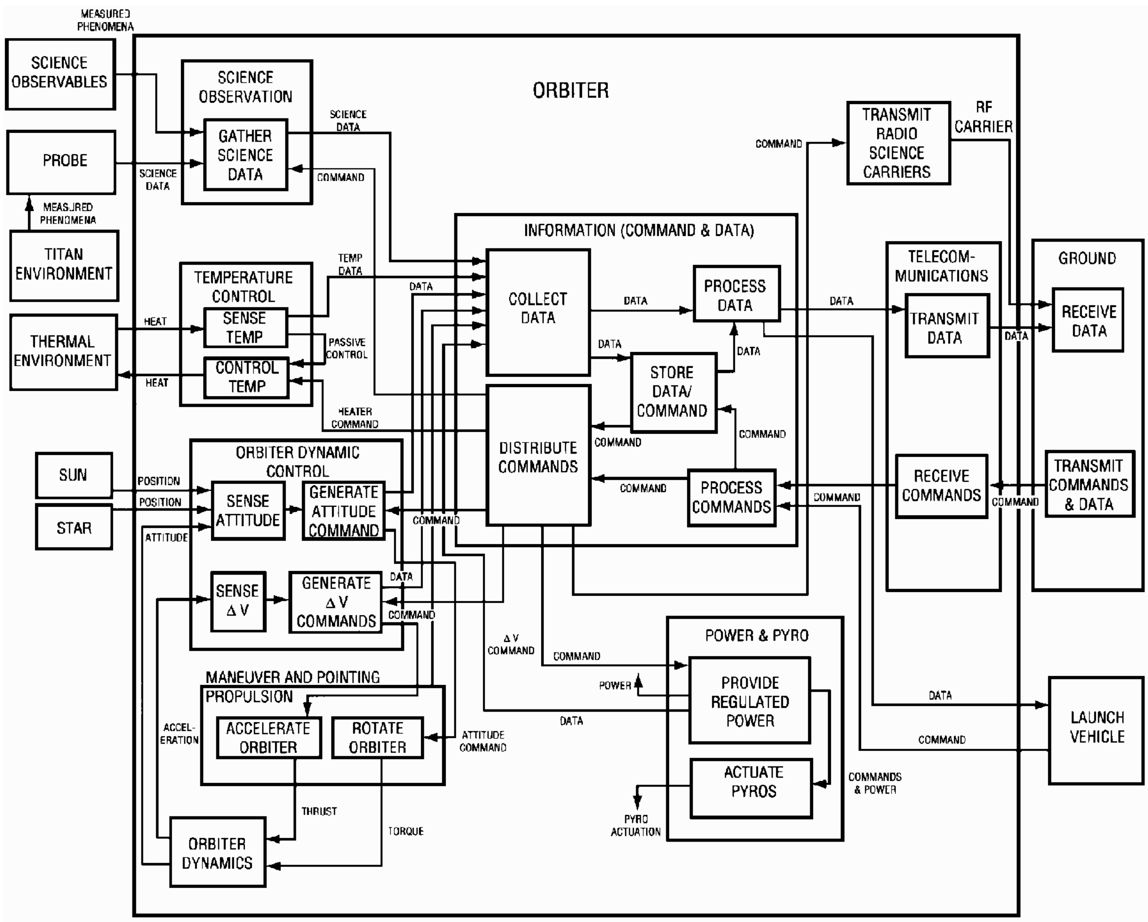

Fig. 6 Orbiter functional block diagram.

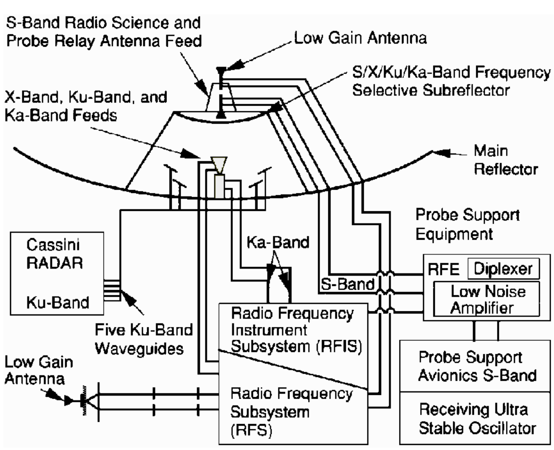

Fig. 7 Orbiter antenna subsystem block diagram, with interconnections.

orbiter solid-state recorders (described in the next section) for later transmission to Earth via the HGA.

Command and Data Subsystem (CDS)

The CDS receives ground commands and memory loads from the RFS, processes them, and distributes them to instruments and other subsystems. It receives data from other subsystems, processes it, formats it for telemetry, supplies Reed–Solomon encoding, and delivers the telemetry to the RFS for transmission to Earth. A pair of redundant MIL-STD-1553B data buses, using packet telemetry, provide communication with other subsystems. Each user interfaces with the data bus through a standard bus interface unit or a remote engineering unit. The communication rate on the bus allocated to data from science instruments is 430×10^3 bps. CDS uses redundant MIL-STD-1750A flight computers. Two 1.8-gigabit solid-state recorders provide mass storage.

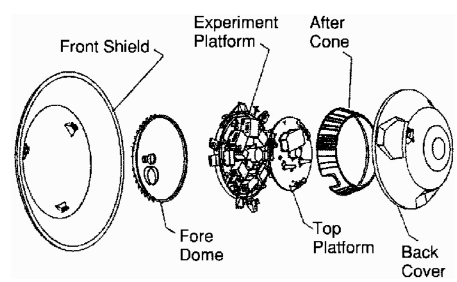

Fig. 8 Huygens Probe, exploded view.

Huygens Probe

The Huygens probe system includes both the probe itself and the Probe Support Equipment. The Probe Support Equipment, which remains attached to the orbiter, supports the probe on one side of the orbiter, spins it up, and ejects it from the orbiter by spring action. It also incorporates an S-band receiver to receive telemetry from the probe after separation, data handling to forward this telemetry to CDS for later transmission to Earth, and an ultrastable oscillator for radio frequency Doppler measurement of probe velocity relative to the orbiter[24] (Fig. 7).

Probe mass is approximately 320 kg. The probe consists of a blunt-nosed, sphere-cone descent module encased in a conical front shield, 2.7 m in diameter, which acts as a decelerator during atmospheric entry, and a back cover (Fig. 8). Shield and cover use silica composites for protection against the high heat flux of entry. Both are jettisonable. Within the descent module, the scientific instruments and most other probe equipment are mounted on an instrument platform. Parachutes are attached to a top platform. The forward dome of the descent module has external spin vanes, and there is a swivel on the parachute harness, so the module will spin during descent to provide scan for its camera.

$LiSO_2$ batteries store 1600 W-h of energy and supply ~250 W for the planned 3 h of probe operation. For thermal control, the probe utilizes multilayer insulation and about 35 W of radioisotope heater units. Command and data management incorporates, for redundancy, both software and hard-wired sequencing of probe events. Included is a triply redundant wake-up timer and a g switch to detect deceleration by Titan's atmosphere. There are also accelerometers (range 10^{-4}–500 m/s^2) to measure both axial deceleration and spin. Redundant frequency-modulated continuous wave radar altimeters measure altitude from 20 km down. Each altimeter transmits 60 mW of radio frequency at 15.4 or 15.8 GHz via a 125 × 162 mm planar slot antenna.

Probe command and data management include 20 kilobits of on-board data storage. Telecommunication after the probe separates from the orbiter is limited to telemetry from probe to orbiter. This is sent to the orbiter via two transmitters with solid-state amplifiers, each having 10-W output at S-band (2.1 GHz), and a wide-beam (±57 deg) antenna. Data rate over the radio link will be 16×10^3 bps. Total data return from the probe is expected to be >175 megabytes.

Scientific Instruments

Orbiter

Twelve scientific instruments are carried by the orbiter. For seven of these, a principal investigator and coinvestigators are responsible for the instrument as well as the scientific investigation. Five are designated as facility instruments to be used by a science team. The instruments are listed in Table 1, which also gives the principal investigator or facility instrument manager for each, as well as mass, power, and output data rate. The science payload mass totals 365 kg. Each instrument has one or more microprocessors that perform internal control and data handling for that instrument.

Instruments: Remote Sensing

Six of the orbiter instruments will measure properties of objects remote from the spacecraft: the Imaging Science Subsystem, Visible and Infrared Mapping Spectrometer, Composite Infrared Spectrometer, Ultraviolet Imaging Spectrograph, Cassini Radar, and Radio Science. The first four of these are mounted and coaligned on the Remote Sensing Pallet, which in turn is mounted on the upper electronics module of the orbiter (Fig. 5).

Imaging Science Subsystem (ISS)

The ISS consists of a wide-angle camera, a narrow-angle camera, and associated electronics. Each camera includes optics, filter-changing mechanism, shutter, and detector head plus associated electronics (Fig. 9). The cameras are used both to acquire scientific data and for optical navigation.

The wide-angle camera has refractive optics, with a focal length of 200 mm, a focal length/diameter ratio (f number) of 3.5, and a 3.5-deg field of view. The narrow-angle camera has Ritchey–Chretien reflective optics, with a 2000-mm focal length, an f number of 10.5, and a 0.35-deg field of view. Filters are mounted in two rotatable wheels per camera. The wide-angle camera has 18 filters over the range 350–1100 nm; the narrow-angle camera has 24 filters from 200 to 1100 nm. Two-blade focal plane shutters control exposure.

The sensing element of each camera is a 1024 × 1024 element CCD, coated with phosphor to provide ultraviolet response and cooled to 180 K by a radiator to reduce dark current. Pixel size is 12 μm. The CCDs provide angular resolution of 60 μrad per pixel for the wide-angle camera and 6.0 μrad per pixel for the narrow angle.

The dynamic range of each camera is about 4000:1, equivalent to 12 bits. Automatic exposure control is available. The data can be reduced to 8 bits per pixel by a lookup table or by reading the 8 least-significant bits. A lossless data compressor provides an average compression ratio of 2:1 or greater. There is also a lossy compressor providing average compression ratios as high as 8:1. Editing can be used to sum adjacent pixels or to transmit partial frames. References 25 and 26 give additional information about ISS.

Visible and Infrared Mapping Spectrometer (VIMS)

The VIMS will furnish information about the surface and atmospheric composition of Saturn and its satellites. It provides images in which every pixel contains high-resolution spectra of the corresponding spot on the ground. VIMS maps the areas viewed with lower spatial resolution than ISS but at 352 contiguous wavelengths between 0.35 μm and 5.1 μm.

VIMS has separate infrared and visible sensor channels. The infrared and visible sensors are mounted on a VIMS optical pallet, which in turn mounts to the spacecraft's remote sensing pallet

Table 1 Cassini orbiter investigations/instruments

Investigation	Principal Investigator (PI) or Instrument Manager (IM)[a]	Mass, kg	Typical peak power, W	Maximum data rate, bps ($\times 10^3$)
Cassini Plasma Spectrometer (CAPS)	David Young (PI) Southwest Research Institute	21.4	21.0	16.0
Cosmic Dust Analyzer (CDA)	Eberhard Grün (PI) Max-Planck Institut für Kernphysik	16.7	19.5	0.5
Composite Infrared Spectrometer (CIRS)	Virgil Kunde (PI) Goddard Space Flight Center	44.3	32.5	6.0
Ion and Neutral Mass Spectrometer (INMS)	Jack Richards (IM) Goddard Space Flight Center	13.0	31.0	1.5
Imaging Science Subsystem (ISS)	Thomas Livermore /William Harris (IM) Jet Propulsion Laboratory	61.1	70.8	366.0
Dual Technique Magnetometer (MAG)	David Southwood (PI) Imperial College	9.8	13.0	2.0
Magnetospheric Imaging Instrument (MIMI)	Stamatios Krimigis (PI) Applied Physics Laboratory, Johns Hopkins University	28.5	26.1	8.0
Cassini Radar (RADAR)	Young Park/Mimi Paller (IM) Jet Propulsion Laboratory	56.7	120.0	365.0
Radio and Plasma Wave Science (RPWS)	Donald Gurnett (PI) University of Iowa	39.0	18.3	370.0
Radio Science (RS)	Carole Hamilton (IM) Jet Propulsion Laboratory	15.5	89.0	0.0
Ultraviolet Imaging Spectrograph (UVIS)	Larry Esposito (PI) University of Colorado	16.0	14.0	31.0
Visible and Infrared Mapping Spectrometer (VIMS)	David Juergens (IM) Jet Propulsion Laboratory	40.1	29.2	183.0
Total		361.9	——[b]	——[c]

[a]The five instruments for which an IM is listed are facility instruments.
[b]Instruments are not at peak power at the same time.
[c]Instruments are not at maximum data rates at the same time.

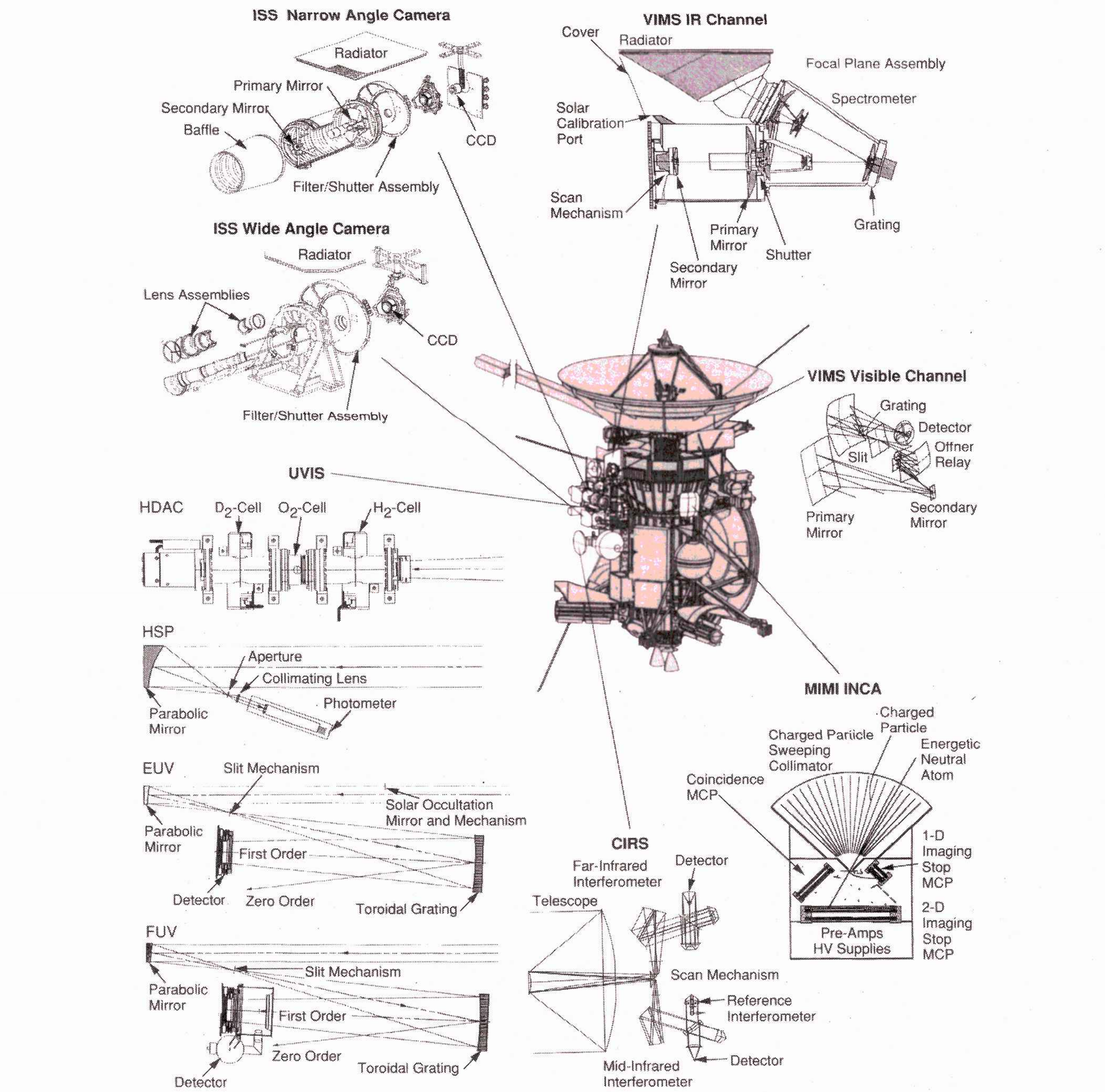

Fig. 9 Orbiter remote sensing instruments.

(Figs. 5 and 9). Major VIMS assemblies are supplied by the United States, Italy, and France.

The infrared channel covers wavelengths 0.85–5.1 μm. Its optics include an $f/3.5$ Ritchey–Chretien telescope with an aperture of 230 mm and a secondary mirror that scans on two axes to produce 64×64 pixels, each a square 0.5×0.5 mrad, in a field 1.9×1.9 deg. Other scan patterns can be commanded. Radiation gathered by the telescope passes through a shutter, spectrometer slit, and collimator to a diffraction grating, which disperses it in wavelength. A camera with reflective optics refocuses it onto a linear detector array of 256 indium antimonide photodiodes. Each receives an image of the field of view in a separate waveband 16.6 nm wide. Spectral blocking filters, on a sapphire substrate, are located in front of the detectors to eliminate higher order spectra. The detector array is cooled by a radiator to as low as 56 K. The spectrometer operating temperature is 125 K.

The visible channel produces multispectral images spanning the spectral range from 0.35 to 1.05 μm. It utilizes a Shafer telescope, an Offner relay, and a holographic grating spectrometer. The silicon CCD array detector is cooled to 190 K by a radiator. One dimension of the array provides spectral separation into 96 wave bands. The other provides linear spatial separation. The primary mirror is pivoted to scan the scene about one axis perpendicular to the array spatial dimension. The resulting data are 96 two-dimensional images of the same region, each in a separate spectral band 7.3 nm wide. The visible channel generates square 0.5×0.5 mrad pixels to match those of the infrared channel.[27–29]

Composite Infrared Spectrometer (CIRS)

CIRS measures planetary radiation from 10 to 1400 cm^{-1} (1000 to 7 μm) in three spectral bands. The CIRS optics assembly includes a telescope, three interferometers, a spectral scan mechanism, and an 80 K cooler. The telescope is a 50.8-cm Cassegrainian (Fig. 9).

The far infrared interferometer (10 to 600 cm^{-1}, 1000 to 17 μm) is responsive to both wavelength and polarization. It has an input polarizer, a polarizing beam splitter, and an output analyzer. The polarizer and analyzer are substrate-mounted wire grids. This interferometer has two thermopile detectors, each with a concentrator. Its field of view is 4.3 mrad in diameter. Spectral resolution is 0.5–20 cm^{-1}.

The mid-infrared interferometer is a conventional Michelson covering the range 600 to 1400 cm^{-1} (17 to 7 μm). It employs a Ge lens to focus the interferometer output on two focal planes. One has a 1 × 10 linear array of photoconductive HgCdTe detectors covering the range 600–1100 cm^{-1}. The other uses a 1 × 10 linear array of photovoltaic HgCdTe detectors covering 1100–1400 cm^{-1}. The field of view of each detector is about 0.27 × 0.27 mrad. Spectral resolution is 0.5–20 cm^{-1}.

The motor-driven scan mechanism moves reflecting elements in one dimension to change the path lengths of the three interferometers and hence their passbands. The third or reference interferometer uses the mid-infrared optical path and provides a servo signal to ensure that the motor scans at uniform velocity.

The mid-infrared detector arrays are mounted on an 80 K cooler. Other portions of the optics assembly are cooled to 170 K by a separate radiator. To reduce heat leakage into the cold optics assembly, special wires with low thermal conductance are used for its electrical leads.[30]

Ultraviolet Imaging Spectrograph (UVIS)

The UVIS instrument measures, spectroscopically analyzes, and images ultraviolet emissions at brightness levels of 0.001 Rayleigh to several thousand Rayleighs. UVIS is a two-channel spectrograph [far ultraviolet (FUV) and extreme ultraviolet (EUV)] and includes a hydrogen deuterium absorption cell (HDAC) and a high-speed photometer (HSP) (Fig. 9).

Each of the two spectrographic channels utilizes a reflecting telescope, a concave grating spectrometer, and an imaging, pulse-counting detector. The telescope primary is an off-axis parabolic section with a focal length of 100 mm, a 22 × 30 mm aperture, and a field of view of 3.67 × 0.34 deg. The aberration-corrected toroidal grating focuses the spectrum onto an imaging microchannel plate detector (MCP).

The far-ultraviolet channel has a wavelength range of 115–190 nm. Selectable entrance slits provide 2.4 Å resolution. The range of the extreme ultraviolet channel is 55–115 nm, with spectral resolution available as narrow as 2.1 Å. This channel also contains a mechanism that allows sunlight to enter the telescope when the sun is 20 deg off axis; this is used to observe solar occultations.

The high-speed photometer measures undispersed (zero order) light from its own parabolic mirror with a photomultiplier tube detector. The wavelength range for this photometer channel is 115–185 nm; the field of view is 0.34 × 0.34 deg.

The hydrogen deuterium absorption cell is a photometer that measures hydrogen and deuterium concentrations. Behind an objective lens, it has three resonance absorption cells. One is filled with hydrogen and another is filled with deuterium. A tungsten filament in each of these cells dissociates a fraction of the molecular gas and allows the hydrogen/deuterium spectrum near the resonance lines to be measured to high resolution by varying the filament temperature. An oxygen cell is used to selectively transmit Lyman α lines while attenuating nearby wavelengths. A channel electron multiplier detects photons not absorbed in the cells.[31]

Cassini Radar (RADAR)

The RADAR is designed for observation of the surface of Titan during close flybys of that satellite. It operates at Ku-band. The radar includes a radio frequency electronics subsystem (Fig. 5), a digital subsystem, and a power conditioner (Fig. 10). The radar utilizes the orbiter's HGA. It can be switched from one to another of five Ku-band feeds (microstrip arrays) (Fig. 7). Four of these feeds are offset from the antenna axis and generate four side-looking beams. One feed on-axis provides a narrower central beam. A frequency-selective subreflector transmits the radar Ku frequency but reflects the X-band communications frequency.

The instrument has five operating states: high-resolution synthetic aperture imaging, low-resolution synthetic aperture imaging, altimetry, scatterometry, and radiometry. Its peak radio frequency output is 63 W. For radiometry measurements, the radar does not transmit but it receives blackbody radiation from the surface of Titan. The radar formats, compresses, and buffers its scientific data and then forwards it to the orbiter command and data handling subsystem as the bus data rate permits.[32,33]

Radio Science Instrument (RS)

Orbiter RS measurements will provide data on the atmospheres and ionospheres of Saturn and Titan, on the rings, and on the gravity fields and ephemerides of Saturn and its satellites. During cruise, the instrumentation will be used to search for gravitational waves, in a general relativity measurement, and to obtain electron densities of the solar corona.

The RS investigation employs both the X-band communications link of the spacecraft RFS and the Ka- and S-band capabilities of the Radio Frequency Instrument Subsystem (RFIS). RFS equipment used includes a transponder, a traveling wave tube (TWT) amplifier, and an ultrastable oscillator. The RFIS contains an S-band transmitter and a suite of Ka-band equipment: a phase-lock loop translator that receives and translates the uplink carrier by a factor of 14/15 for retransmission back to Earth, an exciter that generates a downlink signal, and a TWT amplifier. Transmission and reception are by the HGA. Downlinks with accurately known frequency can be transmitted by the X-band TWT amplifier, the Ka-band exciter and amplifier, and the S-band transmitter. Two-way coherent signals are provided by X-band uplink to the transponder and by Ka-band uplink to the translator in conjunction with the X and Ka downlinks mentioned. Capabilities include one- and two-way Doppler, differential one-way ranging, and two-way ranging. Links are with 34- and 70-m antenna Earth stations of the Deep Space Network. Figure 11 is a block diagram of the RS equipment.

Radio frequency output at Ka- and S-bands is 10 W. Frequency stability of transmissions ($\Delta f/f$), set by the ultrastable oscillator, is better than 1×10^{-13} for integration times of 10–10,000 s. Allan deviation of Ka-band transmissions is $<1 \times 10^{-15}$. Two-way ranging provides an accuracy of 20–30 ns (6–9 m) (Ref. 34).

Instruments: Fields, Particles, and Waves

Six instruments that observe fields, particles, and plasma waves are the Dual Technique Magnetometer, Radio and Plasma Wave Science, Cassini Plasma Spectrometer, Magnetospheric Imaging Instrument, Cosmic Dust Analyzer, and Ion and Neutral Mass Spectrometer.

Dual Technique Magnetometer (MAG)

The Dual Technique Magnetometer measures the magnetic field vector. It consists of a three-axis Flux Gate Magnetometer (FGM)

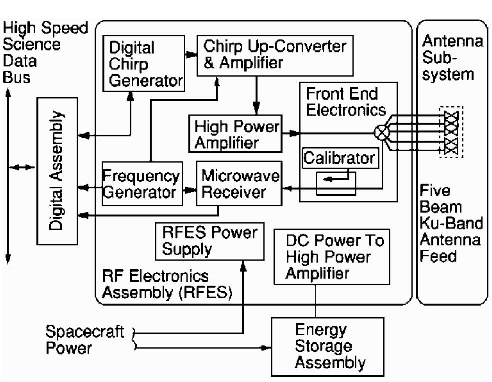

Fig. 10 Orbiter Radar, functional block diagram.

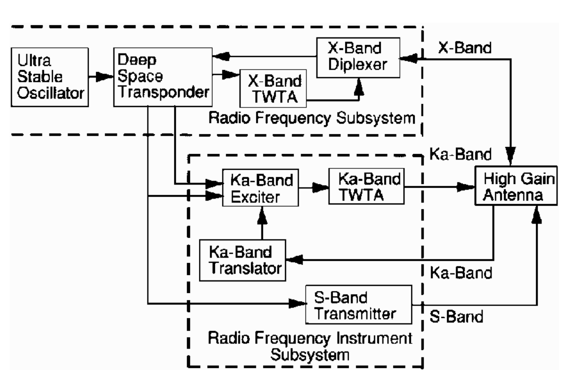

Fig. 11 Radio Science instrument, block diagram.

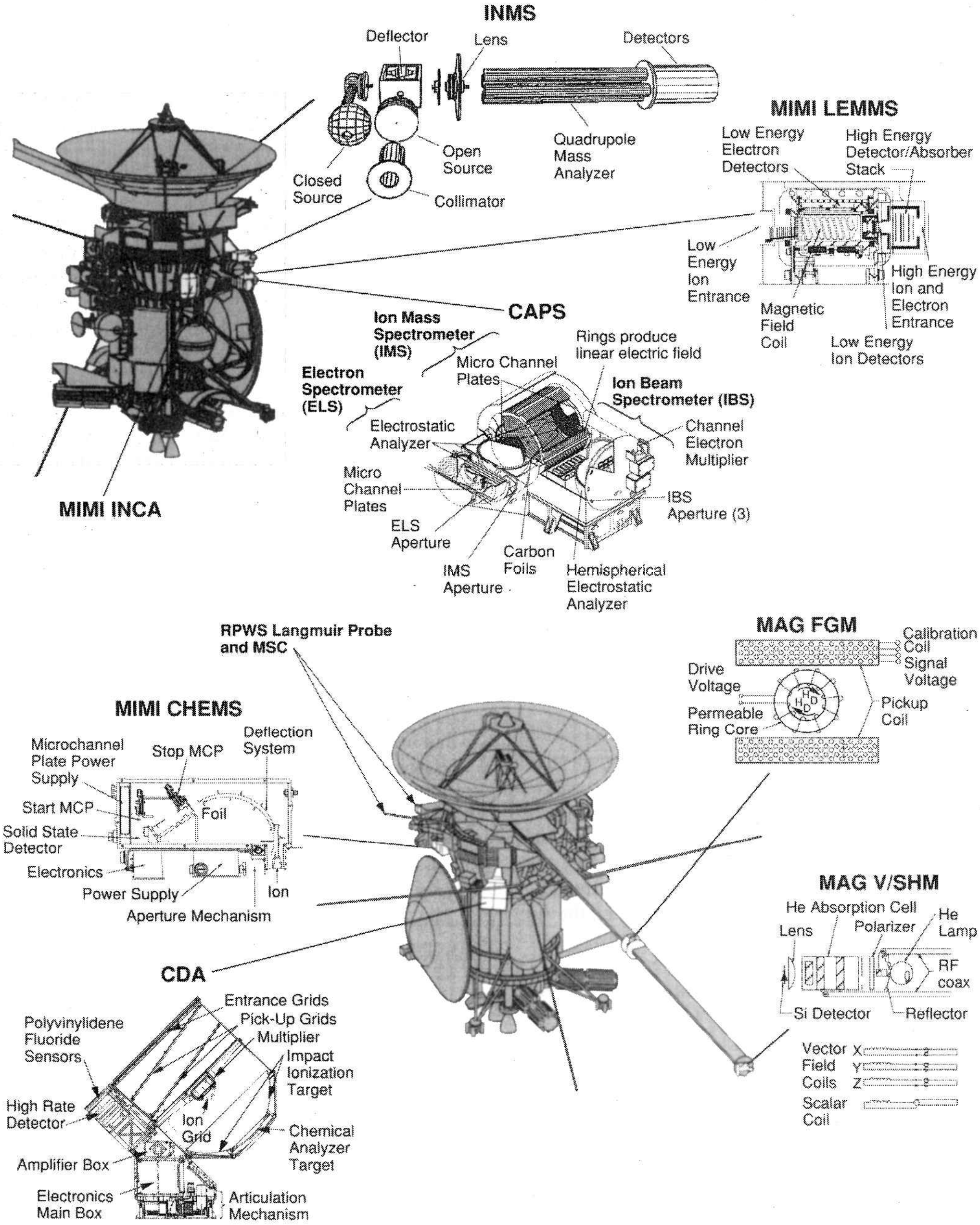

Fig. 12 Orbiter fields, particles, and waves instruments.

and a Helium Magnetometer. The Vector/Scalar Helium Magnetometer (V/SHM) measures the magnitude of the magnetic field or, alternatively, its three orthogonal components. The magnetometer boom supports the V/SHM at its outboard end and the FGM near its midpoint. Magnetometer electronics are in a spacecraft bay.

Operation of the V/SHM is based on field-dependent light absorption (the Zeeman effect) and optical pumping. Radio frequency excitation of a lamp filled with helium at low pressure generates infrared light, which passes through a polarizer and an absorption cell to a silicon detector (Fig. 12). Helium in the absorption cell is excited by radio frequency discharge to produce metastable atoms. Net optical pumping in the cell is maximum when no magnetic field is present; the presence of a field reduces optical pumping and results in increased absorption. For vector field measurements, the absorption is modulated by a rotating sweep field generated by triaxial Helmholtz coils. Detector output components at the sweep frequency are nulled by feedback through the Helmholtz coils, providing a measurement of all three components of the ambient field vector. Scalar field measurements utilize a separate coil whose output is frequency modulated. A component of the detector output signal is related to the Larmor frequency, which is directly proportional to the magnetic field.

The FGM has three identical sensors, oriented orthogonally to each other (Fig. 12). In each, a permeable ring core is wound with a coil operating at 18 kHz, which drives the core to saturation. A pickup coil surrounds the core. The presence of an ambient field component parallel to the coil axis causes the core saturation to become unsymmetrical and induces a second harmonic in the pickup coil that is proportional to the ambient field component.

The use of two separate magnetometers at different locations aids in distinguishing the ambient magnetic field from that produced by the spacecraft. The V/SHM provides highest sensitivity at frequencies up to 1 or 2 Hz; the FGM is useful at 1–20 Hz. They have full-scale ranges of 32–44,000 nT (Ref. 35).

Radio and Plasma Wave Science (RPWS)

The RPWS instrument will measure ac electric and magnetic fields in the plasma of the interplanetary medium and Saturn's magnetosphere, as well as electron density and temperature. Sensors include an electric antenna, a magnetic search coil assembly, and a Langmuir probe (Figs. 5 and 12). The antenna consists of three elements arranged as a dipole and a monopole and mounted on the upper equipment module of the orbiter. Each is a collapsible tube, which is rolled up for launch and subsequently unrolled to its 10-m

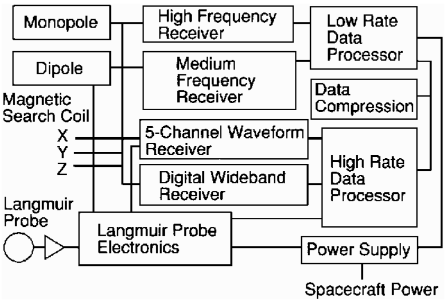

Fig. 13 Radio and Plasma Wave Science instrument, block diagram.

length by a motor drive. The magnetic search coil assembly includes three orthogonal coils about 25 mm in diameter and 260 mm long, each with a high-permeability core, a main winding, and a feedback winding, and mounted on a small platform attached to a HGA support. The Langmuir probe, which measures electron density and temperature, is a metallic sphere 50 mm in diameter attached to the coil platform by a 1-m deployable boom. Signals from these sensors go to high- and medium-frequency receivers, a wideband receiver, and a five-channel waveform receiver (Fig. 13). Ranges are 1 Hz to 16 MHz for electric fields, 1 Hz to 12.6 kHz for magnetic fields, electron densities of 5 to 10,000 e/cm^3, and electron temperatures equivalent to 0.1 to 4 eV. Sensitivity to electric fields at 1 kHz is 0.4 μV narrow band, 100 nV/Hz$^{-1/2}$ wideband; at 20 kHz, it is 0.1 μV narrow band, 5 nV/Hz$^{-1/2}$ wideband. Sensitivity to magnetic fields at 1 kHz is 0.03 pT narrow band and 0.007 pT/Hz$^{-1/2}$ wideband. Dynamic range is >90 dB.

RPWS also has a sounder mode. Square wave pulses are generated and transmitted by the antenna to stimulate plasma resonances. The received signals are analyzed to give electron densities.[36]

Cassini Plasma Spectrometer (CAPS)

The CAPS measures composition, density, flow velocity, and temperature of ions and electrons in Saturn's magnetosphere, using three sensors: an Ion Mass Spectrometer (IMS), an Ion Beam Spectrometer (IBS), and an Electron Spectrometer (ELS). A motor-driven actuator rotates the sensor package to provide 208-deg scanning in azimuth about the symmetry axis of the orbiter (Fig. 12).

The ELS uses a "top hat" curved-plate electrostatic analyzer and MCP detectors for electron energy measurements. The ELS energy range is 0.7–30,000 eV with a resolution (ΔE/E) of 0.17. The sensor's field of view is 5×160 deg and angular resolution is 5×20 deg.

The IBS uses a hemispherical curved-plate electrostatic analyzer and channel electron multiplier detectors to determine energy/charge ratios. The energy range of the IBS is 1 eV to 50 keV, and energy resolution is 0.015. Field of view is 1.5×160 deg, and angular resolution is 1.5×1.5 deg.

The IMS provides data on both energy/charge and mass/charge ratios. A top hat curved-plate electrostatic analyzer provides energy/charge separation. The ions are then accelerated electrostatically to strike and penetrate a set of thin carbon foils. This produces secondary electrons and breaks up some of the molecular ions. Secondary electrons strike a MCP and signal the start of an ion's time of flight. The ions travel in a chamber in which the electric field increases linearly along the analyzer length. Positive ions with less than 15 keV of kinetic energy are deflected back to the entrance end of the analyzer where they strike a MCP, stopping the time-of-flight timer. Because of the quadratic electrical potential, these ions experience simple harmonic motion and their time of flight is a function only of their mass/charge ratio and is independent of their entry energy and direction. The quadratic electrical potential also permits high mass resolution. Positive ions with higher energy, negative ions, and neutrals strike another MCP at the opposite end. Fragments resulting from breakup of molecular ions supply information on their composition.

The mass range of the IMS is 1–60 amu; its mass resolution ($\Delta m/m$) is 0.013. The energy range is 1 eV to 50 keV, with a resolution of 0.17. Field of view is 12×160 deg, and angular resolution is 12×20 deg. Reference 37 gives further information about CAPS.

Megnetospheric Imaging Instrument (MIMI)

The MIMI will provide images of the plasma surrounding Saturn and determine ion charge and composition. Like CAPS, it has three sensors. One of these, the Low-Energy Magnetospheric Measurements System (LEMMS) (Fig. 12), has ion-implanted solid-state detectors to provide directional and energy information on electrons at 15 keV to 10.5 MeV, protons at 15 to 130 MeV, and other ions at 20 keV to 10.5 MeV per nucleon. The LEMMS head is double-ended, with oppositely directed 15- and 45-deg conical fields of view. LEMMS is mounted on a platform that permits continuous rotation of the head through 360 deg on an axis perpendicular to the orbiter HGA axis and to the LEMMS telescope axis.

Another sensor, the Charge-Energy-Mass Spectrometer (CHEMS) (Fig. 12), measures charge and composition of ions at 10–265 keV/e with an electrostatic analyzer, a time-of-flight mass spectrometer, and MCPs. Its mass/charge range is 1–60 amu/e (elements H to Fe) and molecular ion mass range is 2–120 amu. Energy resolution [(ΔE/Q)/(E/Q)] is 0.05 and mass resolution ($\Delta m/m$) is 0.11. The CHEMS head has a $\pm 80 \times 6$ deg field of view.

The third MIMI sensor, the Ion and Neutral Camera (INCA) (Fig. 9), is a time-of-flight camera with collimator slits, an entrance foil, and MCPs. It records ions and neutral molecules with energies from 10 keV to about 8 MeV per nucleon and provides remote images of the energetic neutral emission of Saturn's magnetosphere. Although MIMI is listed as a fields and particles instrument, INCA might also be classified as a remote sensor. It is bore-sighted with the optical remote sensing instruments. INCA has a $\pm 60 \times \pm 45$ deg field of view and an angular resolution of about 2×2 deg.

Cosmic Dust Analyzer (CDA)

The CDA measures flux, velocity, charge, mass, and composition of dust and ice particles in the mass range 10^{-16}–10^{-6} g. It has two types of sensors: high-rate detectors and a dust analyzer[38] (Fig. 12). The two high-rate detectors use depolarization of polyvinylidene difluoride film by impacting particles to count impacts up to 10,000 per s. These detectors are intended primarily for measurements in Saturn's rings. One of them has a film 28 μm thick with an area of 50 cm^2. The other has film 6 μm thick and an area of 10 cm^2. Their counting rates give the integral flux of dust particles above the mass threshold of each high-rate detector. The threshold varies with impact velocity, but ring particles are in near circular orbits so their velocity at a given point does not vary much.

The dust analyzer determines the electric charge carried by dust particles, the flight direction and impact speed, mass, and chemical composition, at rates up to 1 particle per s and for speeds of 1–100 km/s. Two pickup grids at its entrance register particle charge; charge-sensitive amplifiers and a logarithmic amplifier permit recording over a range of 10^{-16}–10^{-12} C. Most of the incoming particles then strike an impact ionization target. This target is at 0 V potential. An ion collector grid at -350 V accelerates the positive ions of the impact plasma. Many pass through the grid to an electron multiplier detector. Timing of the signals from the three elements indicates the impact velocity; pulse heights indicate the dust particle mass.

Other dust particles strike a separate chemical analyzer target in the dust analyzer and also produce impact ionization. This target is at $+1000$ V and has a grounded grid in front of it to accelerate positive ions. Ions reaching the grid signal the start time for the time-of-flight mass spectrometer. Others pass through into the spectrometer and eventually reach the ion collector and electron multiplier. Their time of flight is an inverse function of the ion mass. The distribution of ion masses (atomic weights) gives the chemical composition of the dust particle. Mass resolution of the ion spectrum ($\Delta m/m$) is approximately 50.

An articulation mechanism permits the sensors to be rotated to several positions relative to the orbiter body.

Ion and Neutral Mass Spectrometer (INMS)

The INMS will determine the chemical, elemental, and isotopic composition of the gaseous and volatile components of the neutral particles and the low-energy ions in Titan's atmosphere and ionosphere, Saturn's magnetosphere, and the ring environment. It will also determine the gas velocity.

Principal subsystems of INMS are two ion sources, an electrostatic quadrupole deflector, a quadrupole mass analyzer, and a detector (Fig. 12).

Ions of the plasma are analyzed as they enter, but neutral molecules must first be ionized within the instrument. In the open ion source, incoming neutral molecules and atoms are collimated into a beam and then ionized by impact of electrons from an electron gun. This source is used primarily for components that might react if allowed to strike instrument surfaces. The closed-ion source uses ram density enhancement to increase sensitivity and accuracy for the more inert atomic and molecular species. Ram enhancement is achieved by limiting the gas conductance from an enclosed antechamber while maintaining a high flux into the chamber. The maximum density enhancement will be ×45 at mass 28 amu for a 5.4 km/s spacecraft velocity. As in the open source, the neutral molecules are ionized by electron impact.

Thermal and suprathermal ions of the plasma surrounding the spacecraft enter INMS through the collimator of the open source.

Ions emerging from the ion sources are directed into the mass analyzer by a 90-deg quadrupole deflector. The mass analyzer is a quadrupole mass filter. As ions exit the analyzer they go into an ion detector (two secondary electron multipliers), which feeds a pulse counter.

The field-of-view of the open source for neutral species is a 16-deg conical full angle; the closed source has a hemispherical field of view. The mass range of INMS is 1–8 and 12–99 amu. The density range for neutral gas is 10–10^{12} molecules per cm^3. Sensitivity for neutral molecules is 2.5×10^{-3} counts per molecule per cm^3-s, and for ions it is 1×10^{-3} counts per ion per cm^3-s.

Probe

The six instruments on the Huygens probe are the Huygens Atmospheric Structure Instrument, Aerosol Collector Pyrolyzer, Gas Chromatograph/Mass Spectrometer, Descent Imager/Spectral Radiometer, Doppler Wind Experiment, and Surface Science Package (Fig. 14). They include a total of 39 sensors. Table 2 lists for each the principal investigator and the instrument mass, power, energy consumption, and data rate. Total mass of the Probe science payload is 48 kg (Ref. 16).

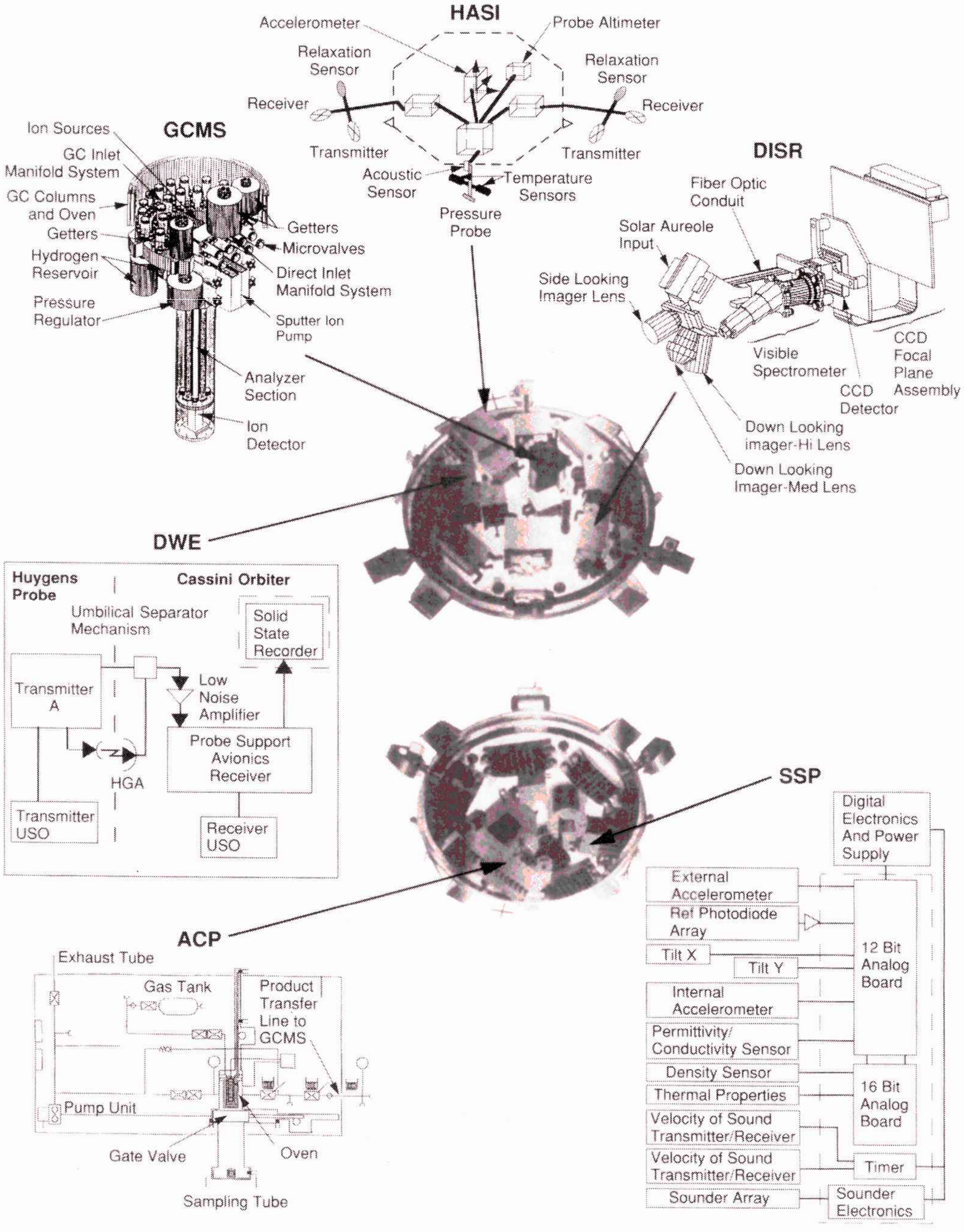

Fig. 14 Huygens Probe experiment platform and instruments.

Table 2 Huygens probe investigations/instruments

Investigation	Principal investigator	Mass, kg	Peak power, W	Energy, W-h	Maximum data rate, bps
Aerosol Collector Pyrolyzer (ACP)	Guy Israel Service d' Aeronomie Verrierès le Buisson	6.7	13.3/71.5[a]	69.8	128
Descent Imager/Spectral Radiometer (DISR)	Martin Tomasko University of Arizona	8.5	39.8	45.7	4800
Doppler Wind Experiment (DWE)	Michael Bird Universitat Bonn	2.1	18.6	25	10
Gas Chromatograph/Mass Spectrometer (GCMS)	Hasso Niemann Goddard Space Flight Center	19.5	44.5	110	960
Huygens Atmospheric Structure Instrument (HASI)	Marcello Fulchignoni Observatoire de Paris	6.7	22.5	41	896
Surface Science Package (SSP)	John Zarnecki University of Kent	4.2	17.2	26	704
Total		47.7	——[b]	317.5	——[c]

[a]ACP is allocated two power lines.
[b]Instruments are not at peak power at the same time.
[c]Instruments are not at maximum data rates at the same time.

Huygens Atmospheric Structure Instrument (HASI)

The HASI includes a variety of sensors (Fig. 14). Atmospheric pressure sensors have a resolution of $\pm 0.04\%$ or ± 0.005 millibar; atmospheric temperature sensors have a resolution better than 0.02 K below 110 K and 0.07 K at higher temperatures. For determination of atmospheric density, a servo accelerometer measures acceleration along the spin axis over full-scale ranges of 2 mg to 18.5 g, with a resolution 0.05% of full scale. Three piezoresistive accelerometers measure acceleration along all three axes of the probe over a range of ± 20 g with a resolution of ± 50 mg.

A microphone senses acoustic noise from thunder, precipitation, and turbulence. A permittivity and wave analyzer includes an electrode array to measure permittivity and electrical conductivity of the atmosphere and surface. It senses electric fields at frequencies from dc to 10 kHz. HASI also processes the IF signal from the probe's radar altimeter to obtain information on surface topography, structure, roughness, and electrical properties.

Aerosol Collector Pyrolyzer (ACP)

The ACP will pump several samples of Titan's atmosphere through a filter to collect aerosols. Samples are obtained through a sampling device extended beyond the boundary layer of the probe. The filter is then transferred to an oven heated to successively higher temperatures, up to 600–700°C, to vaporize and pyrolyze the collected material. The effluent produced at each temperature is swept up by nitrogen carrier gas and transferred to the GCMS for analysis[39] (Fig. 14).

Gas Chromatograph/Mass Spectrometer (GCMS)

The GCMS will provide quantitative analysis, including isotopic analysis, of the atmosphere. Atmospheric samples are transferred into the instrument by dynamic pressure as the Probe descends through the atmosphere. Samples obtained at high altitudes can be stored for later analysis.

The GCMS contains three chromatographic columns with different absorbers for separation of gases. The mass spectrometer serves as detector for the gas chromatograph, for unseparated atmospheric samples, and for those provided by the ACP and has individual inlets for each of these (Fig. 14). In the mass spectrometer, ionization is by electron impact, separation is by a quadrupole mass analyzer, and ion detection is by a secondary electron multiplier. The mass range is 2–146 amu, detector threshold mixing ratio is 1×10^{-12} (at signal-to-noise ratio $= 1$), and dynamic range is 10^8. Portions of the Probe GCMS and the Orbiter INMS instruments share identical designs.

Descent Imager/Spectral Radiometer (DISR)

The DISR will obtain data on the thermal balance of the atmosphere and surface of Titan; clouds and cloud particles; concentrations of argon and methane; whether the local surface is solid or liquid, and, if solid, its topography. DISR (Fig. 14) includes three framing imagers, looking downward and horizontally, a spectrometer dispersing light from two sets of optics looking downward and upward, and four solar aureole radiometers. All of these output light via fiber optics bundles to different areas of a single 256×520 CCD pixel array. The spectral range of the imagers is 660–1000 nm; their pixel resolution is 0.06–0.20 deg. The spectrometer's range is 480–960 nm, with a pixel spectral resolution of 2.4 nm. The aureole radiometers operate at 475–525 and 910–960 nm and have 1-deg pixel resolution.

Separate downward- and upward-looking optics are linked by fiber optics bundles to an infrared grating spectrometer. The infrared optics include a shutter. The infrared detectors are linear InGaAs photodiode arrays. Spectral range is 870–1700 nm; pixel spectral resolution is 6.3 nm.

There are also violet photometers looking downward and upward. Their detectors are silicon photodiodes. Their bandwidth is 350–470 nm, and each records as a single pixel.

In addition to the sensors, DISR contains a lamp to provide additional illumination of the surface of Titan for measurement of spectral reflectance in the methane absorption bands.

Doppler Wind Experiment (DWE)

The DWE measures the height profile of zonal wind and its turbulence. It utilizes an ultrastable oscillator (USO) on the Probe and another on the Orbiter (Figs. 14 and 7, respectively). The output frequency of each USO is set by a rubidium oscillator. The Probe USO then sets the carrier frequency of one of the Probe's S-band transmitters. The frequency received by the Orbiter for this channel is recorded and stored for transmission to Earth. There it is compared with that of the Orbiter USO, recorded at the same time, to determine the Doppler velocity between Probe and Orbiter.

The long-term frequency stability of each USO ($\Delta f/f$), over the Probe descent time of 2–2.5 h, is better than 2×10^{-10}. The short-term stability (Allan deviation) over 100 s is 1×10^{-12}. Wind will be measured to a precision of 1 m/s. Vertical resolution of wind shear will vary with altitude, from 1800 m at 130-km altitude to about 20 m at the surface.[40]

Surface Science Package (SSP)

The SSP contains sensors to determine the physical properties and composition of the surface (Fig. 14). Among them are two impact accelerometers (piezoelectric), which should indicate whether the surface is solid or liquid. There are two sensors (liquid-filled tubes with electrodes) to measure tilt about two axes after landing. A group of platinum resistance wires, through two of which a heating current can be passed, will measure temperature and thermal conductivity of the surface and lower atmosphere and the heat capacity of the surface material. A pair of piezoelectric transducers, one generating and the other receiving a 1.0-MHz acoustic signal, will measure acoustic velocity. Another transducer, pointed downward and operating at 15 kHz, will conduct acoustic sounding of liquid depth if the Probe lands in liquid.

An opening at the bottom of the Probe body, with a vent extending upward along the Probe axis, will admit liquid. This will fill the space between a pair of electrodes. The capacitance between the electrodes will give the dielectric constant of the liquid; the resistance will give the electrical conductivity. A float, with electrical position sensors, will determine the liquid's density. A sensor to measure refractive index of the liquid has LED light sources, a prism with a curved surface, and a linear photodiode detector array. The position of the light/dark transition on the detector array indicates the refractive index.

Operations

Orbiter

Power available on the Orbiter is not sufficient to operate all instruments and engineering subsystems simultaneously. Orbiter operations are therefore divided into a number of operational modes. In each mode, power is allocated among the instruments and engineering subsystems as appropriate for the operation. Some of the modes are for engineering operations, and some are for gathering scientific data. For example, during much of the orbital tour of Saturn, 16 h in a remote sensing mode will alternate with 8 h in a fields, particles, waves, and downlink mode. In the remote sensing mode, most of the remote sensing instruments will be acquiring data; many of the fields and particles instruments will not. In the fields and particles mode, the reverse will be true. Other science modes will be used during satellite flybys, occultations, cruise to Saturn, etc. Instruments not gathering data generally will not be turned off during the orbital tour but rather will be left in a low-power "sleep" state. This is to reduce on-off thermal cycling, keep high voltages on to avoid a need to turn voltage up slowly each time, and preserve RAM to avoid the need to reload it each time.

The operational modes differ in characteristics other than power. In remote sensing, for example, the Orbiter is oriented to point remote sensing instruments toward their objects of interest. This means that the HGA cannot be pointed toward Earth, so telemetry is stored in the solid-state recorders for transmission later. In the fields, particles, waves, and downlink mode, the HGA is pointed to Earth, permitting transmission of stored and real-time telemetry, and the Orbiter is rolled about the antenna axis at 0.26 deg/s to provide scanning about an axis additional to the articulation axes of some instruments.

The bit rate available on the CDS data bus is not high enough to permit all instruments to output telemetry simultaneously at their maximum rates. The Orbiter is switched among a number of different telemetry modes in which the available bit rate is allocated differently among the instruments.

Probe

There is no radio transmission link to the Huygens Probe after it separates from the Orbiter; it is wholly autonomous. The instruments are turned on in a preprogrammed sequence. Operation is controlled by timers, acceleration sensors, altimeters, and a sun sensor. As in the Orbiter, instruments are switched among various power states and telemetry allocations to stay within the total power and bandwidth available.[16,41,42]

Summary

The Cassini mission will take 18 scientific instruments to Saturn. It uses a Titan IV/Centaur launch vehicle plus two gravity assists from Venus, one from Earth, and one from Jupiter for the seven-year journey. After the spacecraft is inserted into Saturn orbit, it will separate into a Saturn orbiter and an atmospheric probe, called Huygens, which will descend to the surface of Titan. The orbiter will orbit the planet for four years, with close flybys of Enceladus, Dione, Rhea, and Iapetus, and multiple close flybys of Titan.

The orbiter is three-axis stabilized. Its instruments are body-mounted; the spacecraft must be turned to point them toward objects of interest. There are two redundant main engines. Radioactive thermal generators provide 600–800 W of electrical power. Telecommunication is at X-band over a 4-m HGA. The maximum downlink rate from Saturn is 166×10^3 bps. Two solid-state recorders provide 1.8 gigabit each of onboard storage.

The probe is spin stabilized. A heat shield will decelerate it and protect it from heat during entry to Titan's atmosphere. Parachutes will then slow its descent to the surface. $LiSO_2$ batteries supply power. The probe returns its data via an S-band link to the orbiter.

The orbiter carries 12 scientific instruments. Optical instruments provide imagery and spectrometry at wavelengths from 55 nm to 1 mm. A radar instrument supplies synthetic aperture imaging, altimetry, and microwave radiometry. S-, X-, and Ka-band link measurements between orbiter and Earth provide information about intervening material and gravity fields. Field and particle instruments measure magnetic and electric fields, plasma properties, and the flux and properties of dust and ice particles.

The probe carries six instruments. These include sensors to determine atmospheric physical properties and chemical composition. Optical sensors will provide data on temperatures and thermal balance and obtain images of Titan's atmosphere and surface. Doppler measurements over the radio link from probe to orbiter will provide wind profiles. Surface sensors will measure impact acceleration, thermal properties of the surface material, and, if the surface is liquid, its density, refractive index, electrical properties, and acoustic velocity.

Addendum

After the manuscript of this paper was submitted, additional papers concerning Cassini/Huygens were published.[43]

Acknowledgments

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A great many people contributed to the design and construction of the Cassini/Huygens spacecraft. The instruments were designed and built by the Cassini principal investigators, coinvestigators, instrument managers, and the many members of their instrument teams. Much of the information in this paper comes from Cassini project documents prepared by them and by Cassini project instrument engineers, payload accommodations engineers, investigation scientists, and the cognizant engineers of the various engineering subsystems of the spacecraft. The spacecraft design and description are based on work of a spacecraft design team led by spacecraft system engineers Richard Stoller and John Slonski. The orbiter mission information is from material prepared by Cassini mission planners led by Roger Diehl. We also thank those who reviewed the manuscript, including William Fawcett, John Wirth, David Seal, and many of the preceding individuals. Jean-Pierre Lebreton, Michel Verdant, Edward Miller, Cynthia Kahn, Don Mitchell, Nicole Rappaport, and Karen Boyle provided figures. The instrument engineers and payload accommodations engineers contributed to both the work and this paper in many ways. They include Donald Boyd, Kirk Breitenbach, Elizabeth Carrell, Sayan Chakraborty, Barbara Cheney, Ann Dalton, Randy Dodge, Eugene Ehrlich, Craig Elliott, Lisa Evelsizer, Marc Lane, Matthew Marshall, Vickere Murphy, David Newell, Ralph Parrish, Michael Thomas, and Tom Wahl. Cecelia Guiar, Catherine Cagel, Kirk Breitenbach, Allan Conrad, Carl Kloss, and Thomas Tomey provided leadership for the effort. William Fawcett, the Cassini project instrument manager, and Michel Verdant, manager of payload and assembly, test, and verification for the Huygens project, deserve special credit.

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